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Predicting Sediment Transport Dynamics in Ephemeral Channels: A Review of Literature

by Stephen H. Scott

PURPOSE: The goal of this Coastal and Hydraulics Engineering Technical Note (CHETN) is to evaluate state-of-the-art research efforts concerning predicting sediment transport in desert ephemeral channels. The present day methods used to predict sediment transport were primarily formulated for application to perennial flow channels. Additionally, in the development of sediment transport relationships it is assumed that the sediment and water mixture is Newtonian, i.e., a linear relationship exists between the shear stress and the shear rate. Hyperconcentrated sediment flows containing fractions of fine, cohesive sediments may be non-Newtonian in nature. These flows are characterized by a nonlinear relationship between shear rate and shear stress with mixture viscosity a function of shear rate. The transport capacity of a hyperconcentrated non-Newtonian mixture can be much higher than a Newtonian mixture, as well as the capacity of the mixture to transport coarse sediments such as gravels and cobbles. Therefore, the sediment transport processes of erosion, entrainment, transport, and deposition may be quite different for arid region ephemeral channels.

BACKGROUND: Understanding the basic dynamics of sediment transport in arid ephemeral channels such as Las Vegas Wash is necessary for predicting impacts of flood events. Sediment transport characteristics such as erosion and deposition can intensify structural damage and frequency of overbank flooding. For steep, sand bed arroyos, sediment concentrations can exceed 100,000 parts per million (ppm) by weight. Mussetter (1994) reports on a number of studies that show sediment hyperconcentrations are common for steep sand bed channels. Einstein and Chien (1955) found that when the suspended sediment concentration exceeds about 4 percent by volume (~100,000 ppm) the vertical distribution of sands in the water column becomes more uniform and homogeneous with a transport capacity greater than would be expected based on clear water flows. Leopold and Miller (1956) reported concentrations in arroyos in north central New Mexico approaching 200,000 ppm by weight and Nordin (1963) reported concentrations in the Rio Puerco, Paria, and Little Colorado Rivers up to 650,000 ppm by weight, with sand concentrations up to nearly 450,000 ppm by weight. Such high concentrations effectively increase the density of the fluid, thus increasing the force of the flows on in-stream or overbank structures such as bridges, retaining walls, and levees. The recession of flood flows will result in deposition of suspended sediments, thus raising the channel bed and increasing the probability of future overbank flood flows.

The hydrology and sediment transport of arid-region ephemeral channels cannot be reliably predicted by extrapolation of humid region hydrology (McMahon 1979). Spatial and temporal variability in hydrologic processes and the resulting erosion and sedimentation processes are characteristically high in arid and semi-arid regions. Variations in flood magnitude are much greater for ephemeral channel flows as compared to that of perennial channel flows. For example, Graf (1988) reports that for a humid region such as Pennsylvania, the 50-year return flood event is 2.5 times the mean annual flow, whereas the 50-year return flow of the Gila River in Arizona is about 280 times the mean annual flow. Costa (1987) reports that of the 12 largest floods ever measured in the United

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States, all occurred in semi-arid to arid regions, and 10 occurred in regions with less than 400 mm (16 in.) of rainfall. For a given intensity of rainfall, desert environments produce more runoff per unit area than in temperate regions. Arid channel floodplains are generally deficient in vegetation, thus promoting runoff. Typically, soils in these areas are commonly more compacted than in humid regions, thus rainfall does not infiltrate into the soil as readily (Thornes 1994).

In ephemeral channels of the Southwestern United States, sediment often moves in a step-wise manner because of transmission losses (Renard 1975). Water from storms originating in the upper reaches of a watershed is often completely absorbed in the channel before reaching the outlet. Therefore, the ability of the channel to transport sediment is dependent on varying flow as a function of distance along the channel. Sediment that is eroded, entrained, transported, and deposited by one storm may be available to subsequent storm events for transport within the channel. Thus, the transport of sediment in arid ephemeral channels is complicated by flow sequencing.

Because of the lack of rainfall in desert regions, weathering is dominated by mechanical not chemical means, therefore, clay production is inhibited. This results in a predominance of silt-sized fractions in the soils. Clay is an important factor in stabilizing channel banks, which stimulates meandering behavior (University of Aberdeen 2003). The lack of clay in arid ephemeral channels may partially explain why these channels typically have wide, shallow, low sinuosity geometries. Additionally, the lack of cohesive clays in the bed results in a high mobility of sediments during large flow events.

The link between climate and sediment yield was investigated by Langbein and Schumm (1958). They evaluated data from 94 stream sampling stations in the southwest United States. The results of their effort was the Langbein-Schumm rule which shows that the maximum sediment yield occurs at an annual precipitation of about 300 mm / year (12 in.) (semi-arid region). Where precipitation exceeds this, the growth of vegetation is promoted which protects the land surface and thus reducing sediment production and runoff. In drier areas, although vegetation growth is further limited, the available energy for increased erosion and transport is limited.

The most significant morphological changes that occur in fluvial systems is the result of uncommon large magnitude flood events. This is the case for both humid and arid regions, but more so for arid regions where the largest floods are proportionately much larger than the mean than for humid regions. Typical effects of these large events is significant channel widening, channel deepening, high sediment concentrations in the flow, and large amounts of deposition on the floodplains.

RELATED STUDIES: A number of studies have been conducted to measure and quantify bed and suspended load in arid ephemeral channels. The goals of these studies were not directed to formulating predictive functions, but to better understand the fundamental processes that govern transport dynamics of ephemeral channels.

Bed-Load Studies. Reid (1994) presents a series of bed-load measurements resulting from the Northern Negev River Sediment Monitoring Program. The area of interest is the Negev Desert in Israel. This represents the first body of bed-load information to be collected during flash floods in desert gravel-bed streams. The bed-load flux is presented as a function of hydraulic parameters such as depth, hydraulic radius, water-surface slope, discharge, bed shear stress, and stream power. A series of related studies on bed-load transport in arid ephemeral channels were reported by: Laronne

et al. (1992); Ergenzinger (1994); Laronne et al. (1994); Meirovich (1998); Hassan (1999); Reid et al. (1998); Powell (2001); and Powell et al. (1996).

Suspended Load Studies. A number of suspended sediment transport investigations are found in the literature. Alexandrov (2003) presents suspended sediment concentration as a function of flash flood discharge for the northern Negev Desert in Israel. The data were collected using a preprogrammed pump sampler. Mean suspended sediment concentrations of 34,000 mg/L were measured, with minimum and maximum concentrations of 21,000 – 229,000 mg/L. A regression relationship was fit to the data, however, only 50 percent of the variance in suspended sediment concentration is explained by variations in the discharge. Reid (1987) investigated suspended sediment transport characteristics of the Il Kimere drainage basin in Northern Kenya. He reported on measured suspended sediment concentrations and sediment size classes. His findings indicate that the correlation between flow and sediment concentration is generally good well into the coarse sand size class, and that the size distribution of the flash flood sediments is controlled by the flow. Related studies in the literature include Frostick (1983), Dunkerley (1999), Bourke (2002), and Sharma et al. (1984).

PREDICTING SEDIMENT TRANSPORT IN ARID EPHEMERAL CHANNELS: A majority of the publications on sediment transport studies in ephemeral channels were concerned with either describing qualitative changes in channel morphology or attempting to measure suspended or bed load resulting from high intensity short duration flows common to desert regions. Only a few of the reported studies attempted to correlate sediment load measurements to existing or newly formulated predictive expressions. The following text provides a short description of the research efforts for predicting sediment transport in arid ephemeral channels. Essentially three existing sediment transport correlations have been reported in the literature as being somewhat successful in predicting sediment transport in ephemeral channels. Lane (1982) presents a sediment transport formulation to compute sediment transport capacity. The model computes both bed load and suspended load for multiple size fractions. It is essentially a modification of the Duboys-Straub formula (see Graf (1971)) for a complete description). The transport capacity for bed-load particles is computed by:

$$g_{sb}\left(D_i\right) = \alpha f_i B_5\left(D_i\right)\tau\left[\tau - \tau_c\left(D_i\right)\right] \tag{1}$$

With g_{sb} (D_i) the bed-load transport capacity per unit width for particles of size D_i, α is a weighting factor to insure that the sum of the individual transport capacities equals the total transport capacity computed using the median particle size; f_i is the proportion of particles in size class i; d_i is the diameter of particles in size class I; B_5 (d_i) is the sediment transport coefficient; τ is the bed shear stress; and τ_c (D_i) is the critical shear stress for particles in size class i. The transport capacity for suspended load is based on the concept of stream power (Bagnold (1956, 1966):

$$i_s = p\frac{e_s u_s}{v_s}\left(1 - e_b\right) \tag{2}$$

with i_s the suspended sediment transport rate per unit width, P the available stream power per unit area of the bed, e_s the suspended load efficiency factor, e_b the bed-load efficiency factor, u_s the transport velocity of the suspended load, and v_s the settling velocity of the particles. The total load is then computed as the sum of the bed load from Equation 1 and the suspended load from Equation 2.

The model was fitted to data representing 27 observations at the Niobrara River in Nebraska (Colby and Hembree 1955). The predicted and measured sediment discharged discharge rates agreed well for the limited data presented in this study. The size distribution of sediments was not provided for this particular application.

Frostick (1983) described a study of an ephemeral stream network (approximately 7 sq km) in the northern arid zone of Kenya, Africa. Water and sediment discharge were analyzed in detail over several flood events. Peak sediment concentrations up to 15,800 mg/L were measured. Comparison between expected concentrations in size classes above 63 microns (.0024 in.) using Laursen's semi-empirical equation (Laursen 1958) and observed sediment concentrations results in a high correlation coefficient, $R = 0.88$, however the relationship is poor for silt and clay fractions which constituted approximately 56 percent of annual suspended sediment discharge. Laursen's equation is presented as follows:

$$C = 0.01\gamma \sum_i P_i \left(\frac{D_i}{d}\right)^{7/6} \left(\frac{\tau_l}{\tau_{ci}} - 1\right) f\left(\frac{u_*}{w_i}\right) \tag{3}$$

with C the total average sediment concentration in weight per unit volume, γ the specific weight of water, P_i the proportion of size class i, D_i the sediment size, d the depth, τ_l Laursen's bed shear stress due to grain resistance, τ_{ci} the critical bed shear stress for size class i, U_* the shear velocity near bed, and w_i the fall velocity for size class i. Laursen's bed shear stress due to grain resistance is defined as follows:

$$\tau_l = \frac{\rho U^2}{58}\left(\frac{D_{50}}{d}\right)^{1/3} \tag{4}$$

with ρ the mass density of water, U the average flow velocity, and D_{50} the median grain size. The expression $f\,(u_*/w_i)$ in Equation 3 is a graphical function that is presented as a function of u_*/w_i.

Renard (1974 and 1975) applied the Laursen sediment transport relation to Walnut Gulch, an ephemeral stream discharging into the San Pedro River in southeastern Arizona. For this application, the model was verified for mean particle sizes of 1.0 to 1.5 mm (0.04 – 0.06 in.). For simplification purposes, the stream cross section was assumed rectangular. The authors justified this assumption because ephemeral channels are often wide and shallow with width-depth ratios greater than 50. Results indicate that the Laursen sediment transport relationship used with the Manning open channel flow relationship in a rectangular channel predicted sediment discharge that agreed closely with values obtained by sediment sampling on the Walnut Gulch experimental watershed. The results were sensitive to the bed material size distribution and to the roughness term used in the Manning relation.

A number of predictive bed-load sediment transport equations were rated against a set of field data collected by automatic samplers during flash flood events in channels on the northern Negev Desert in Israel (Reid et al. 1996). The data originated from five to six flash floods with rise times of 10 min or less and a few hours duration. Annual rainfall in this region is about 220-280 mm/year (9-11 in.). The data were collected on gravel-bed streams with an average longitudinal slope of 0.0087. The

median grain size (*D50*) of the surface layer in the channel proper was 6 mm (0.24 in.), while the channel bars had a median grain size of about 20 mm (0.79 in.).

Five bed-load equations were rated against the data set: Meyer Peter Muller (1948); Parker (1979); Parker (1990); Bagnold (1980); and Parker et al. (1982). They were chosen because they are commonly used by practicing engineers. The bed load measured during this study was 1.6 times higher than previous bed-load measurements presented by Laronne and Reid (1993) and Reid and Laronne (1995) where the effects of high concentrations of suspended sediment on fluid density were incorporated in a buoyancy factor that was applied to the data. The Meyer Peter Muller (MPM) equation fit the data best within the limited scatter of the data field. The authors theorize that because the gravel-bed channels found in this region are not armored, the MPM equation was appropriate to use because it is primarily based on flume studies with nonarmored channels. The Parker data (1979) also fit the data well. The Bagnold equation underpredicted bed load, however, the upper limit of bed-load transport ascribed to streams by Bagnold was much less than the transport rates reported in the Yatir Channel. The Parker equation (1982) significantly underpredicted the data. This equation assumes that sediment supply originates from a subarmor layer, inferring that an armored layer must be breached before significant transport occurs. The Yatir Channel was not armored, thus the sediment was readily available to the flow.

Mussetter (1994) described the development of a bed material transport predictive relationship for sediment transport under high concentration conditions typical of steep, sand bed arroyos. This formulation addresses important concerns about predicting sediment transport when concentrations exceed the limit for a Newtonian carrier fluid. Mussetter references a numerical solution to the diffusion equation that accounts for the effects of suspended sediment concentration on the fall velocity, fluid viscosity, and eddy diffusivity.

The solution developed by Woo was linked to the MPM bed-load equation to provide an improved relationship for estimating bed material transport capacity (bed and suspended load) in steep, sand bed streams where the suspended sand concentration is expected to be high. Muesetter applied the Woo/MPM model over a range of conditions typical of arroyos found in the southwestern United States. From these applications, Muesetter then developed a simplified power function relationship that was developed by regression techniques. The function is of the following form:

$$q_s = aV^bY^c\left(1-\frac{C_f}{10^6}\right)^d \tag{5}$$

with q_s the unit bed material transport capacity, V the flow velocity, Y the flow depth, C_f the fine sediment concentration in parts per million by weight, exponents b, c, and d, and coefficient a. The coefficient and exponents vary with the median bed material size.

CONCLUSIONS: Many of the papers published on the subject of sediment transport in ephemeral channels deal with data collection techniques and predicting morphology change. Only a select few of the papers found during this literature search applied or made reference to applying, testing, or developing predictive relationships to ephemeral channel sediment transport.

The most often referred to sediment transport formulas are those developed by Meyer Peter Muller and Laursen. None of the papers that were reviewed presented applications to comprehensive data sets. Most of the applications were specific to individual regions, channels, and sediment types. Based on these reviews, general guidance can be formulated. For gravel bed ephemeral channels, the Meyer Peter Muller (1948) and the Parker (1979) functions may be applicable. If the gravel bed does not have an armored surface layer, then the MPM method is preferable. For armored gravel bed streams the Parker formulation may be a better predictor. For sand bed ephemeral channels for which suspended sediment concentrations are at 10,000 ppm or below, the Laursen transport function may be applicable. In many steep sand bed ephemeral channels with a significant fine sediment load, the density and viscosity of the carrier fluid can significantly change the sediment transport capacity of the stream. For predicting sediment transport in streams that may have suspended sediment concentrations within the range of 10,000 ppm to 400,000 ppm, it seems logical that the predictive function should take into account the effects of changing fluid properties on carrying capacity. In this light, the formulation presented by Mussetter (1994) would be an appropriate approach to predicting sediment transport.

POINT OF CONTACT: For additional information, contact Dr. Stephen Scott (601-634-2371, email: *Steve.H.Scott@erdc.usace.army.mil*) of the Coastal and Hydraulics Laboratory, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

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